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MICHELSON-MORLEY EXPERIMENT WITHIN THE QUANTUM MECHANICS FRAMEWORK

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Abstract

It is revisited the Michelson-Morley experiment within the quantum mechanics framework. One can define the wave function of photon in the whole space at a given moment of time. The phase difference between the source and receiver is a distance between the source and receiver at the time of reception hence it does not depend on the velocity of the frame. Then one can explain the null result of the Michelson-Morley experiment within the quantum mechanics framework.

The Maxwell-Lorentz equations describe electromagnetic field as a wave propagating with the velocity c. It is reasonable to think that electromagnetic wave propagates with the velocity c with respect to a privilege frame. If some frame moves with the velocity v with respect to a privilege frame then one can expect that electromagnetic wave propagates with the velocity $\vec{c} - \vec{v}$ with respect to the moving frame. The Michelson-Morley experiment was suggested to determine the velocity of electromagnetic wave with respect to a moving frame with the earth being taken as a moving frame. However the Michelson-Morley experiment [1] yielded the null result. The special relativity [1] explains the null result of the Michelson-Morley experiment with the Lorentz transformation for coordinates of space and time. Electromagnetic field is a quantum object. Below we shall revisit the Michelson-Morley experiment within the quantum mechanics framework.

Consider electromagnetic field within the Newtonian framework. Consider electromagnetic field as a wave with the vector potential $\vec{A}$ in the Euclidean space and time of a privilege frame. We shall take the cosmic microwave background radiation (CMB) [2] as a privilege frame. The Maxwell-Lorentz equations for the electromagnetic wave are given by [3]

$$\triangle\vec{A} - \frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2} = 0 \tag{1}$$

where c is the velocity of light. One can represent the solution of eq. (1) as a plane monochromatic wave

$$\vec{A} = \vec{A}_0 e^{-i\phi} \tag{2}$$

with the phase

$$\phi = \omega t - kr \tag{3}$$

where ω is the frequency, k is the wave vector.

In the quantum mechanics [4], one can consider electromagnetic field as a bunch of photons with the momentum and energy given by respectively

$$p = \hbar k \qquad \mathcal{E} = \hbar\omega \tag{4}$$

where $\hbar$ is the Planck constant. One can conceive the photon as a particle exhibiting wave behaviour. In the quantum mechanics the wave given by eq. (2) is thought of as a wave function of photon associated with a single photon. For photons the Heisenberg uncertainty principle holds true

$$\Delta p \Delta r \geq \frac{\hbar}{2} \qquad \Delta\mathcal{E}\Delta t \geq \frac{\hbar}{2}. \tag{5}$$

In view of eq. (4), the Heisenberg uncertainty principle restricts the wave function of photon in the space and time.

Consider the photon as a particle with the momentum p at the time t. Introduce the wave function of photon with the wave vector $k = p/\hbar$. In the stationary state the momentum of photon is fixed. Then the uncertainty in momentum is $\Delta p = 0$, the uncertainty in the wave vector is $\Delta k = \Delta p/\hbar = 0$. ¿From eq. (5) it follows the uncertainty in space coordinate $\Delta r = \infty$. This means one cannot specify the space coordinate hence one can consider the wave function of photon with the wave vector $k = p/\hbar$ in the whole space at the time t. One can describe the wave function of photon by eq. (2) like the classical wave. However one cannot treat electromagnetic field as a classical wave and conceive it as a fluid consisting of a number of photons. One can treat electromagnetic field as a wave function accompanying to a single photon.

Consider propagation of a photon between the source and receiver. We shall regard the case when the region of propagation of photon is much more than the wave length of photon $\Delta r \gg \lambda = 1/k$. Then one can think of the photon as a point-like quasi-classical particle propagating with the velocity c with respect to the CMB frame. In view of the above reasoning one can define the wave function of photon in the whole space at the time of reception. Then the phase difference between the source and receiver is a distance between the source and receiver at the time of reception

$$\Delta\phi = \phi_r(t_r) - \phi_s(t_r) = k[r_r(t_r) - r_s(t_r)]. \tag{6}$$

We come to the definition of phase within the quantum mechanics framework. In the classical physics the phase is defined through the space coordinate of the source at the time of emission $r_s(t_e)$. In the quantum mechanics the phase is defined through the space coordinate of the source at the time of reception $r_s(t_r)$. The quantum mechanics definition of phase proceeds from the fact that the wave function of photon is associated with a single photon hence is defined in the whole space at the time of reception.

Consider the Michelson-Morley experiment in a frame moving with the velocity v with respect to the CMB frame. Suppose that electromagnetic field (photon) moves with the velocity c with respect to the CMB frame independently of the source (receiver). Then the travel time is a function of the velocity of the frame with the maximum difference of travel time between two legs for two-way travel being $\Delta t = (l/c)(v^2/c^2)$ where l is the length of the leg. According to the quantum mechanics [4] a single photon interferes with itself. The wave function of photon is a superposition of the waves specified along two different legs with the photon as a particle moving along one of the legs. In view of eq. (6), the phase difference between the source and receiver is a distance between the source and receiver at the time of reception. If the lengths of the legs are not the same there is a phase shift between two waves specified along two different legs $\Delta\phi = k(l_2 - l_1)$. When determining the distance between the source and receiver at one and the same moment of time it does not depend on the velocity of the frame. Hence the phase difference between the source and receiver does not depend on the velocity of the frame. Hence there is no phase shift due to the velocity of the frame between two waves specified along two different legs. Thus one can explain the null result of the Michelson-Morley experiment within the quantum mechanics framework without invoking the Lorentz transformation.

According to the special relativity [1] coordinates of space and time follow the Lorentz transformation (LT), $r' = r\mathrm{LT}$, $t' = t\mathrm{LT}$ while the wave vector and frequency of electromagnetic wave follow the inverse Lorentz transformation $k' = k\mathrm{LT}^{-1}$, $\omega' = \omega\mathrm{LT}^{-1}$. Here the non-primed values are the proper ones while the primed values are the apparent ones. The phase of electromagnetic wave is Lorentz invariant $\phi' = \omega' t' - k' r' = \omega t - kr = \phi$ that explains the null result of the Michelson-Morley experiment.

Explanation of the null result of the Michelson-Morley experiment within the quantum mechanics framework allows Galilean invariance of the electromagnetic wave. One may treat the phase given by eq. (6) as Galilean invariant. That is both observers in a privilege and in a moving frames determine the same space coordinate difference and the same wave vector. The wave vector of the electromagnetic wave emitted in a moving frame is Lorentz shifted in a privilege frame (Doppler effect). Assume that electromagnetic wave behaves in a different way under propagation of the electromagnetic wave and under interaction with the source. Under propagation electromagnetic wave is Galilean invariant while under interaction with the source is Lorentz invariant. Then we may apply the conventional special relativity under interaction of the electromagnetic wave with the source. After emission the wave vector of the electromagnetic wave is the same for both observers in a privilege and in a moving frames. That is Galilean invariance of the phase under propagation of the electromagnetic wave means $\phi = k'r =$ Gal inv.

So putting the quantum mechanics definition of the wave function of photon one can explain the null result of the Michelson-Morley experiment without invoking the Lorentz transformation. It is reasonable to assume that under propagation electromagnetic wave is Galilean invariant. Explanation of the Doppler effect needs the Lorentz transformation. It is reasonable to assume that under interaction with the source electromagnetic wave is Lorentz invariant.

References

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